

Extraction of the $\pi^+\pi^-$ Subsystem in Diffractively Produced $\pi^-\pi^+\pi^-$ at COMPASS

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The COMPASS experiment at CERN has collected a large data sample of 50 million diffractively produced $\pi^-\pi^+\pi^-$ events using a 190 GeV/c negatively charged hadron beam. The partial-wave analysis (PWA) of these high-precision data reveals previously unseen details. The PWA, which is currently limited by systematic uncertainties, is based on an isobar model, where multi-particle decays are described as subsequent two-body decays and where a prior-knowledge parametrization for the intermediate two-pion resonances has to be assumed – usually a Breit-Wigner amplitude – thus increasing systematic uncertainties, due to the concrete choice of the parametrization. We present a novel method, which allows to extract isobar amplitudes directly from the data in a less biased way. The focus lies on the scalar $\pi^+\pi^-$ subsystem, where a previous analysis found a signal for a new axial-vector state $a_1(1420)$ decaying into $f_0(980)\pi$.

KEYWORDS: COMPASS, Partial-Wave Analysis, Isobar Model, $a_1(1420)$

1. Introduction

COMPASS is a two-stage multi-purpose spectrometer, located at CERN's Prévessin site, which employs secondary hadron or tertiary muon beams from the Super Proton Synchrotron. Its large acceptance over a wide kinematic range allows COMPASS to study a broad physics program including, amongst others, light-meson spectroscopy, which is the focus here.

The particular channel of interest is $\pi^-p \rightarrow \pi^-\pi^+\pi^-p$, for which COMPASS collected a data set consisting of approximately 50 million events.

2. Analysis method

2.1 The Isobar Model

To analyze the process $\pi^-p \rightarrow X^-p \rightarrow \pi^-\pi^+\pi^-p$ we use the isobar model, which assumes that the appearing intermediate 3π state X^- does not decay directly into $\pi^-\pi^+\pi^-$, but undergoes subsequent two-particle decays until it ends up in the final state: $X^- \rightarrow \xi^0\pi^- \rightarrow \pi^-\pi^+\pi^-$. The intermediate two-pion state ξ^0 is called the isobar.

2.2 Conventional PWA

The conventional PWA expands the complex decay amplitude, which describes the measured intensity distribution \mathcal{I} , into partial waves [1]:

$$\mathcal{I}(\vec{\tau}; m_{3\pi}, t') = \left| \sum_{\text{waves}} \mathcal{T}_{\text{wave}}(m_{3\pi}, t') \Psi_{\text{wave}}(\vec{\tau}; m_{3\pi}) \right|^2. \quad (1)$$

The production amplitudes $\mathcal{T}_{\text{wave}}$ depend on the invariant mass $m_{3\pi}$ of the $\pi^-\pi^+\pi^-$ system and on the reduced squared four-momentum transfer t' . They are fitted to the data in bins of their kinematic variables using an extended maximum likelihood fit.

For constant $m_{3\pi}$ and t' , the decay amplitudes Ψ_{wave} depend on 5 kinematic variables, that define the 3π kinematics and are represented by $\vec{\tau}$, while the angular part alone is given by $\vec{\Theta}$. The decay amplitudes are known functions, which have to be put into the analysis model beforehand. They consist of a mass-dependent part $\Delta_\xi(m_{\pi^+\pi^-})$ which depends on the mass of the $\pi^+\pi^-$ subsystem, and an angular part $\mathcal{K}(\vec{\Theta})$:

$$\Psi_{\text{wave}}(\vec{\tau}; m_{3\pi}) = \Delta_\xi(m_{\pi^+\pi^-}; m_{3\pi}) \mathcal{K}(\vec{\Theta}; m_{3\pi}) + (\text{Bose symm.}). \quad (2)$$

The angular-momentum quantum numbers appearing in a partial wave completely determine the function $\mathcal{K}(\vec{\Theta})$.

The complex function $\Delta_\xi(m_{\pi^+\pi^-}; m_{3\pi})$ describes the complex amplitude of the corresponding isobar ξ and usually has to be known without any free parameters. In the simplest cases, single Breit-Wigner amplitudes are used. Since no unique parametrizations for these amplitudes are given by theory and different models are available, the choice of a particular parametrization introduces a model bias.

A conventional PWA of this type, which was performed on the data-set collected by the COMPASS spectrometer, uses a set of 88 waves [1].

2.3 Freed-isobar PWA

In order to circumvent this problem we introduce a novel method, which was inspired by Ref. [2]. This method allows us to extract isobar amplitudes in bins of $m_{\pi^+\pi^-}$ directly from the data. To this end, the fixed parametrizations are replaced by sets of piece-wise constant functions:

$$\Pi_{\text{bin}}(m_{\pi^+\pi^-}) = \begin{cases} 1 & \text{if } m_{\pi^+\pi^-} \text{ lies in the corresponding mass bin,} \\ 0 & \text{otherwise.} \end{cases} \quad (3)$$

These binned functions replace the fixed isobar amplitudes:

$$\Delta_\xi(m_{\pi^+\pi^-}) \rightarrow \sum_{\text{bins}} \Pi_{\text{bin}}(m_{\pi^+\pi^-}). \quad (4)$$

The set of bins covers the whole kinematically allowed $m_{\pi^+\pi^-}$ mass range. With this replacement, equation (1) reads:

$$\mathcal{I}(m_{\pi^+\pi^-}, \vec{\Theta}; m_{3\pi}, t') = \left| \sum_{\text{waves}} \sum_{\text{bins}} \mathcal{T}_{\text{wave}}(m_{\pi^+\pi^-}^{\text{bin}}; m_{3\pi}, t') \left[\Pi_{\text{bin}}(m_{\pi^+\pi^-}) \mathcal{K}_{\text{wave}}(\vec{\Theta}) \right] + (\text{Bose symm.}) \right|^2. \quad (5)$$

The piece-wise constant isobar amplitudes effectively behave like independent partial waves and their corresponding production amplitudes now also encode information about the $m_{\pi^+\pi^-}$ dependence of the isobar amplitudes. Therefore, the same fit procedure as in the conventional approach can be used. We call this new approach *freed-isobar* PWA.

A freed-isobar wave is named after the following scheme:

$$J^{PC} M^\epsilon [\pi\pi]_{J_\xi^{PC}} \pi L, \quad (6)$$

where J^{PC} are the spin and eigenvalues und parity and generalized charge conjugation of the 3π system, while M^ϵ are its spin projection and reflectivity. The term $[\pi\pi]$ denotes a freed-isobar wave with spin and eigenvalues und parity and charge conjugation of J_ξ^{PC} . Finally, L is the orbital angular momentum between the isobar and the bachelor π .

3. First Application

The analysis presented in the following employs 3 freed-isobar waves: $0^{-+}0^{+}[\pi\pi]_{0^{++}}\pi S$, $1^{++}0^{+}[\pi\pi]_{0^{++}}\pi P$ and $2^{-+}0^{+}[\pi\pi]_{0^{++}}\pi D$. Due to quantum numbers of the $\pi^{+}\pi^{-}$ subsystem, these waves describe seven waves in the conventional scheme. Therefore, the final model consists of 81 fixed and 3 freed-isobar waves.

3.1 $0^{-+}0^{+}[\pi\pi]_{0^{++}}\pi S$ Wave

The $0^{-+}0^{+}[\pi\pi]_{0^{++}}\pi S$ wave is able to describe all three isobars that are used in the conventional PWA: the $f_0(500)$, the $f_0(980)$, and the $f_0(1500)$. Fig. 1 shows the two-dimensional intensity distribution

$|\mathcal{T}_{\text{wave}}(m_{3\pi}, m_{\pi^{+}\pi^{-}})|^2$ for this wave for two bins in t' .

The most striking feature is a peak corresponding to the decay $\pi(1800) \rightarrow f_0(980)\pi$. A smaller peak corresponding to $\pi(1800) \rightarrow f_0(1500)\pi$ is also visible. Broad structures appear at low 2π and 3π masses and low t' , which are probably of mostly non-resonant origin.

Fig. 2 and Fig. 3 show the intensity distributions and Argand diagrams as a function of $m_{\pi^{+}\pi^{-}}$ in narrow $m_{3\pi}$ bins around the $\pi(1800)$ resonance. Peaks and phase motions corresponding to the $f_0(980)$ and the $f_0(1500)$ are visible. They are modulated by the intensity distribution and phase motion of the decay of $\pi(1800)$.

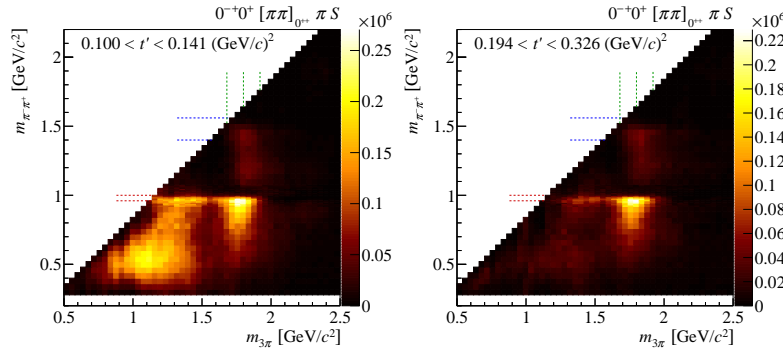


Fig. 1. Intensity distribution of the $0^{-+}0^{+}[\pi\pi]_{0^{++}}\pi S$ wave as a function of $m_{3\pi}$ and $m_{\pi^{+}\pi^{-}}$ for two regions of t' [1].

3.2 $1^{++}0^{+}[\pi\pi]_{0^{++}}\pi P$ Wave

The freed $1^{++}0^{+}[\pi\pi]_{0^{++}}\pi P$ wave is able to describe two waves of the conventional PWA, since the $1^{++}0^{+} f_0(1500)\pi P$ wave was not included in the conventional analysis. The two-dimensional intensity distribution is shown in Fig. 4 for two t' bins. It features a dominant broad structure at low 2π and 3π masses, which moves with t' , indicating a predominantly non-resonant origin. In addition, a narrow peak at $m_{3\pi} \approx 1.4 \text{ GeV}/c^2$ and a $m_{\pi^{+}\pi^{-}} \approx 0.98 \text{ GeV}/c^2$ is visible. It corresponds to the recently discovered $a_1(1420)$ [3]. The observation of this peak in the freed-isobar analysis proves that the $a_1(1420)$ signal is not an artifact of the parametrization of the scalar isobars in the conventional analysis [3].

Fig. 5 shows the 2π intensity distributions below, on, and above the $a_1(1420)$, which exhibits a strong correlation with the $f_0(980)$ peak. A comparison of the $f_0(980)$ mass region from the freed-isobar fit is in good agreement with the intensity of the $1^{++}0^{+} f_0(980)\pi P$ wave from the conventional PWA (See Fig. 6).

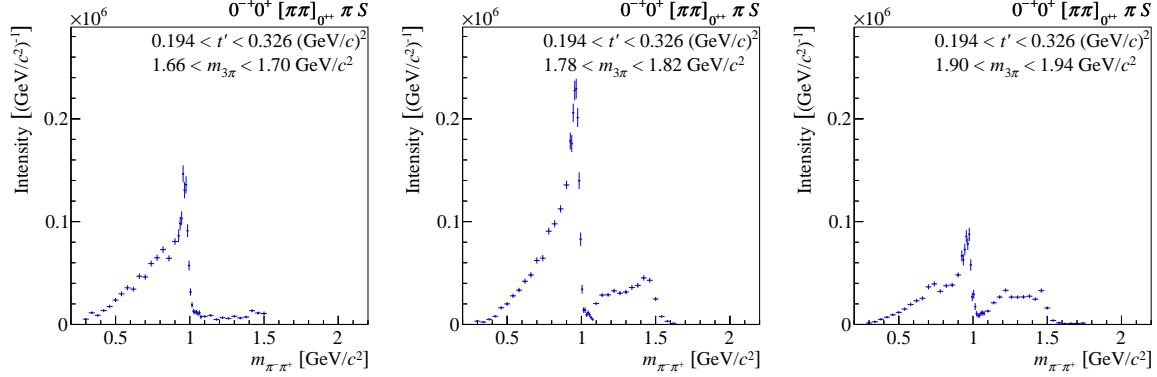


Fig. 2. $0^{-+}0^{+}[\pi\pi]_{0^{++}}\pi S$ intensity distributions for three bins of $m_{3\pi}$, below, on, and above the $\pi(1800)$ resonance [1].

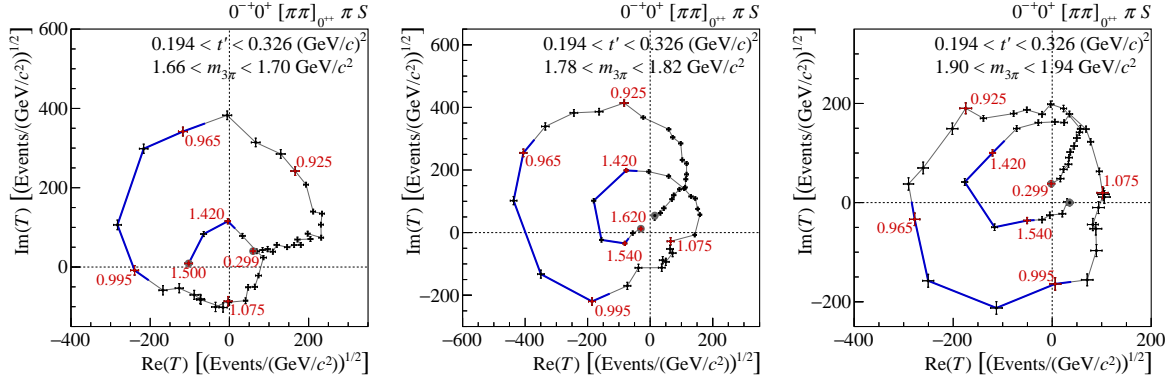


Fig. 3. Argand diagrams of the $0^{-+}0^{+}[\pi\pi]_{0^{++}}\pi S$ amplitude for three bins of $m_{3\pi}$ below, on, and above the $\pi(1800)$ resonance. The $m_{\pi^+\pi^-}$ regions corresponding to the $f_0(980)$ and the $f_0(1500)$ are highlighted in blue [1].

4. Conclusions

We have introduced a novel PWA method for the process $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$ using binned amplitudes to describe the $\pi^+ \pi^-$ subsystems. This not only removes the model bias introduced by formerly fixed amplitudes used for the appearing isobars in the conventional PWA, but also allows us to study the 2π subsystems and their dependence on the 3π source system.

The large data set collected by the COMPASS spectrometer enables us to apply this novel method. In a first analysis, we free the 0^{++} isobar parametrizations for three waves with different J^{PC} of the 3π parent system, namely 0^{++} , 1^{++} , and 2^{-+} . The analysis reproduces most of the expected structures, in particular a peak for the decay $a_1(1420) \rightarrow f_0(980)\pi$, which confirms the new signal observed with the conventional analysis not to be an artifact of the $f_0(980)$ parametrization.

In addition to resonances, broad structures are observed, that typically change their shape with t' . They probably originate from non-resonant processes or from cross-talk with waves, that still employ fixed isobar amplitudes.

We are currently studying the latter effect by increasing the number of freed isobars. At the moment, we aim for a set of 11 freed waves that would describe 75% of the total intensity. In these fits, we encounter several ambiguities in the fit and are currently working on techniques to resolve

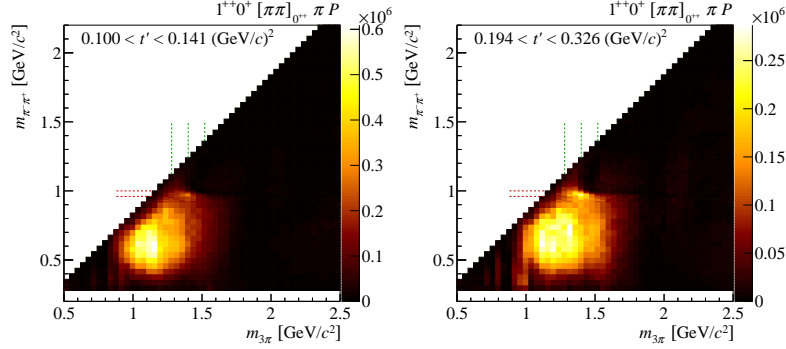


Fig. 4. Intensity distribution of the $1^{++}0^+[\pi\pi]_{0^{++}}\pi P$ wave as a function of $m_{3\pi}$ and $m_{\pi^+\pi^-}$ for two regions of t' [1].

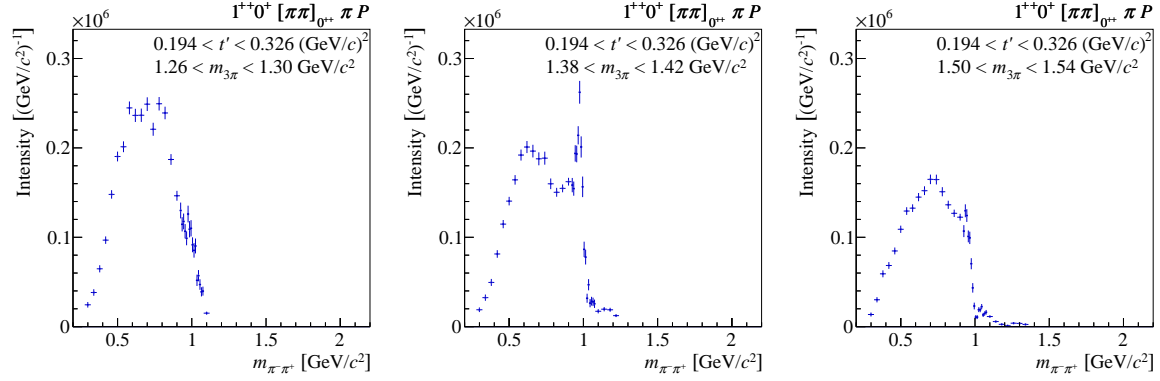


Fig. 5. $1^{++}0^+[\pi\pi]_{0^{++}}\pi P$ intensity distributions for three bins of $m_{3\pi}$ around the $a_1(1420)$ resonance [1].

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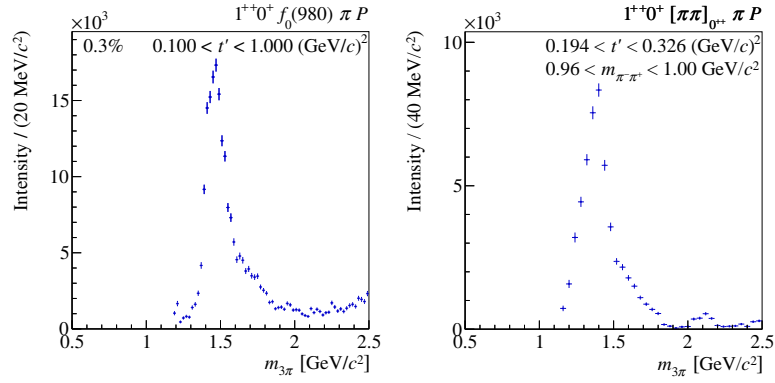


Fig. 6. $1^{++}0^+ f_0(980) \pi P$ intensity from the conventional PWA (left) and intensity sum over the $m_{\pi^+\pi^-}$ bins in the $f_0(980)$ region of the $1^{++}0^+ [\pi\pi]_{0^{++}} \pi P$ wave from the freed-isobar analysis (right) [1].